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Exploring the gaps in renewable energy integration to grid

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Abstract

The continued integration of diverse renewable energy sources into the power grid has led to a significant decrease in power system inertia, thus resulting in several challenges in the electric power system such as frequency instability and sharp rise in rate of change of frequency (rocof). In order to combat these challenges, several technologies such as the use of energy storage systems, hybrid energy storages system and hybrid systems have been used to provide fast frequency response and regulation. This paper gives a comprehensive review of these technologies thus highlighting their applications, merits and demerits for frequency regulation in renewable energy sourced grid. Furthermore, the research reveals that hybridized system provides better characteristics than singly sourced renewable energy system, therefore the best suited hybrid system can be formed based on the desired power grid characteristics and specific power requirement. Finally, it was revealed that FESS, SMES and SCES have similar characteristics, nonetheless, their characteristics is complimentary to that of BESS, CAES and PHES technology, and so a hybrid combination comprising of BESS and SCES could be best suited for fast frequency response in renewable energy sourced grid.

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Keywords: Energy storage system (ESS); Renewable energy sources (RES); System inertia; Rate of change of frequency (rocof); Virtual energy; Synchronous inertia; Inertia constant

1. Introduction

Electric power system has in recent times experienced a gradual but steady drift from conventional synchronous power generators to the use of renewable energy sources (RES) such as photovoltaic (PV), Wind and Hydro power systems due to its comparative advantages [1–5]. Conventional fossil fuel fired generators are associated with increased greenhouse gas emissions, which has led to climate changes and other devastating effect on the globe [6]. On the other hand, renewable energy sources offers clean energy with zero greenhouse gas (GHGs) emission because it non reliant on fossil fuel [7–9], therefore most countries around the world are now trying to

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Nomenclature

RES	Renewable energy sources
BESS	Battery energy storage system
PHES	Pumped Hydro energy storage system
SMES	Superconducting Magnetic Energy Storage
CSP	Concentrated Solar Plant
Li-ion	lithium-ion battery
HTWS	Hydro-thermal-wind-solar
PFC	Power Frequency control
HSS	Hydrogen Storage System
ESS	Energy storage system
SCES	Super capacitor energy storage system
CAES	Compressed air energy storage system
FESS	Flywheel energy storage system
Rocof	Rate of change of frequency
MPPT	Maximum Power Point Tracking
HESS	Hybrid Energy Storage System
AGC	Automatic Generation Control
RE	Renewable energy

meet increasing electricity demand with RES especially PV and wind, while drifting towards a decarbonized power sector.

On the other hand, the increasing integration of RES such as photovoltaic systems and wind turbines into the power grid has led to significant changes in the dynamics of the Electric power system [10–12]. Firstly, the output of renewable energy sources is intermittent which offers a degree of concern [13]. Also, as more renewable energy sourced generators are connected to the power grid through the converters, the overall power system inertia decreases [14,15]. This reduced system inertia has led to decreased power system reliability, grid instability, and frequency instability issues such as high rate of change of frequency (RoCoF) [16,17].

2. Power system operational metrics

In this section, the various parameters that influence the performance of power system particularly in renewable energy sourced grid such as rate of change of frequency (rocof) and system inertia will be highlighted.

2.1. Rate of change of frequency (Rocof)

Rate of change of Frequency (Rocof) can be defined as the measure of frequency deviation within 100 ms to 200 ms after the occurrence of fault or after a sudden imbalance between generated power and load demand [10,18]. High rocof is a challenge of concern in power system as it could led to cascaded loss of generators [19]. Rocof is also closely related with system inertia, as a power system with small inertia is associated with high rate of change of frequency (RoCoF). Therefore, it can be said that frequency stability can only be ensured in a power grid with adequate system inertia [19].

The ROCOF after a loss of generation can be expressed as in Eq. (1).

$$ROCOF = \frac{\Delta P * f}{2S * H} \tag{1}$$

where, S is the rated apparent power, f is the system frequency, H is the inertia constant and ΔP is the change in power of the system.

2.2. Power system inertia

System inertia can be defined as the resistance inherent in the power system to changes in frequency by means of the kinetic energy that is stored in its rotating masses [9]. System inertia plays a vital role in resisting frequency deviations in power system. Previously, generators in the power system were mainly synchronous, therefore the inertia offered by these synchronous machines is called synchronous inertia [15,20]. However, as technology advanced, inertia could also be obtained in renewable energy sources connected with energy storage system and converters; this type of inertia is called artificial or virtual inertia.

2.3. System inertia constant

The inertia constant H can be defined as the time in seconds taken by an electric plant to generate a rated nominal power, from its stored kinetic energy at rated angular speed. The kinetic energy of the synchronous generator can be expressed as in Eq. (2):

$$E_{KE} = \frac{1}{2} J \omega_m^2 \tag{2}$$

where, J is the total moment of inertia in Kg m^2, ω m is the rated mechanical angular velocity in rad/s, and E_{KE} is the kinetic energy stored in its rotating mass.

The inertia constant of the synchronous generator, H, during steady state can therefore be estimated using the swing equation as in Eq. (3);

$$H = \frac{E_{KE}}{S_b} = \frac{\frac{1}{2} J \omega^2 m}{S_b} = \frac{J \omega_m^2}{2 S_b} \tag{3}$$

where J is the total moment of inertia in Kg m^2, W m is the rated mechanical angular velocity in rad/s, and S $_{\mathrm{b}}$ is the selected base apparent power in MVA.

During system disturbance, the imbalance in power is reflected in the rate of change of kinetic energy stored in the generator as shown in Eq. (4).

$$\frac{d}{dt}\left(\frac{1}{2} J \omega_m^2\right) = Pm - Pe \tag{4}$$

where the imbalance in power (Pm–Pe) causes an acceleration or deceleration of the rotor, Pm is the mechanical power applied on the rotor, while Pe is the electrical power of the rotor.

For a power system comprising of several synchronous generators with different ratings, the total inertia constant Hsys can also be expressed as in Eq. (5)

$$H_{Total} = \frac{\sum_{i=1}^{n} H_i S_i}{\sum_{i=1}^{n} S_i} = \frac{\sum_{i=1}^{n} E_{KEi}}{S_{Total}} \tag{5}$$

where, H_i is the inertia constant of the individual synchronous generators, S_i is the generation capacity of the individual generators, n is the total number of power plants, H_{total} is the inertia constant of the whole power system, and S_{total} is the total generation capacity of all generators.

3. Characteristics of synchronous inertia contributing machines to the power grid

This section explains the concept of synchronous inertia and further highlights on the characteristics of various synchronous generators used for providing natural inertia in the power grid.

3.1. Synchronous inertia

Synchronous inertia is provided by conventional synchronous generators. These generators provide frequency regulation (fr) as the stored kinetic energy in their rotating masses opposes changes in frequency in the power grid [1]. The response to a sudden power imbalance in the power grid varies based on the individual characteristics of the synchronous machines such as hydro generator , thermal generators and wind turbine [21]. This section will consider the merit and demerit of the various types of synchronous inertia contributing generators in the power grid.

3.2. Sources of synchronous inertia in power system

Here, various generators which contribute synchronous inertia to the power grid is explained as synchronous inertia could be sourced from both fossil fuel driven generators and renewable energy generators.

Thermal Generators: These are the most common and widely used type of synchronous machines used for power generation. They provide synchronous inertia and can deliver fast frequency response for an average time of 15 min in case of system contingencies. Its inertia constant lies between 2 to 9 s. However thermal generators are associated with pollution (GHGs emission) which causes harmful effect on the environment [1,2,10,22].

Synchronous Condensers: Synchronous condensers are free spinning unloaded synchronous machines with its prime mover removed and having zero real power output. Its inertia constant lies between 1 to 3 s. It provides synchronous inertia and also reactive power compensation in power system. However, synchronous condenser has high maintenance cost, and contribute to environmental noise pollution.

AC Wind Turbine: AC wind turbines are connected directly to the power grid, and they provide a source of synchronous inertia during power imbalance. These machines provide a fast frequency response in power system and offer a clean source of energy, their inertia constant lies between 2 to 6 s [2].

Concentrated Solar Power (CSP): CSP is a promising renewable energy technology which offers a clean source of energy and adds natural inertia to the power grid. They are also cost effective generators which supports RES integration to grid and are often used in a hybridized form such as CSP-BIO plants, CSP-TES, and CSP-PV in order to provide frequency response in a power system [23]. Nonetheless, they are limited by their slow frequency response and high cost of installation [24].

Pumped hydroelectric energy storage: This is a mechanical energy storage system used to provide synchronous inertia, voltage regulation and reactive power support to the grid. PHES has high power ratings and high energy density with an average inertia constant of between 2 and 4 s, however, they are limited by their high cost of installation, small associated inertia and slow frequency response [25,26].

Compressed air energy storage (CAES): This is a promising mechanical energy storage system whose energy depends on the potential energy of pressurized air. CAES is considered a viable ESS because of its high efficiency, high energy density, high power ratings, long life span as it also supports large-scale integration of RES to the grid. It also has Inertia constant of between 3–4 s and provides voltage regulation in power system. Nevertheless, this technology is limited by its complexity in construction, geographical constraint and high cost of installation [27].

Flywheel Energy Storage System (FESS): This is an efficient electro-mechanical energy storage system used to provide fast frequency response within a short response time. FESS has the advantages of high efficiency, high inertia constant, low GHGs emissions, high power density and long life cycle [28]. However, they are limited by their low energy density, and limited energy storage capacity, thus they not suitable for applications requiring continuous power delivery for long period of time. Table 1 shows the detailed characteristics and applications of various generators and energy storage system that contribute synchronous inertia in power system.

4. Contribution of energy storage technologies and hybrid system to power system stability in renewable energy sourced grid

This section introduces the concept of Virtual Synchronous generation (VSG) and further explains various energy storage technologies, hybrid energy storage technologies, and hybrid system used in providing virtual inertia in renewable energy sourced power grid.

4.1. Virtual synchronous generation

This concept is used for providing artificial or virtual inertia into a power system by using an inverter, and energy storage system (ESS) with a suitable control mechanism. VSG concept simply mimics the dynamics of synchronous generators with rotating mass, while the kinetic energy in the rotating mass of synchronous generators is compensated for by the energy stored in energy storage system (ESS) [32].

Table 1. Characteristics and applications of synchronous inertia generators.

Energy storage system	Merits	Demerits	Application	Hybridized Form	Refs.
Concentrated Solar Power (CSP)	Can be used at night unlike PV	High cost of installation, complex construction, slow frequency response	Large power application, Supports RE integration	CSP-TES, CSP-PV, CSP-BIO	[23,24,29, 30]
Pumped hydroelectric energy storage: (PHES)	Has higher energy rating, higher power rating, lower cost per kW, long discharge times	Slow frequency response, lower efficiency	Large scale power rated applications, RE Curtailment, Spinning reserves, voltage stability, power–frequency control	WIND-PHES	[27]
Compressed air energy storage (CAES):	Has higher energy rating, higher power rating, long discharge times, lower cost per KW	Slow frequency response, lower efficiency	Large scale power rated applications, RE Curtailment	HTWS–CAES	[27]
Flywheel Energy Storage System (FESS):	Fast frequency response, longer life span (15–20 years), high efficiency (85%), high power density (1000–2000 W/L)	Low-energy density, high capital cost (5000 $/kWh)	Space Aircraft, light rail systems, power and frequency stability, power quality improvement, RE curtailment	FESS–BESS, FESS–CAES, WIND–FESS, PV-FESS	[31]

4.2. Virtual inertia provision by renewable energy sources

Renewable energy sources such as PV and DC wind turbine have been used to provide virtual inertia and frequency regulation in power system. PV system do not inherently provide system inertia because they have no rotating mass and are only connected to the grid through power electronics converters. However, they can be made to provide frequency regulation when operated in deloading mode [33]. This technique is however limited because it provides slow frequency response with a delay of between 50 and 100 ms, and it is less economically viable compared to BESS connected PV system [34]. On the other hand, like PV system, DC Wind turbines do not inherently provide system inertia, and can also be operated in deloading mode in order to provide frequency regulation. Nonetheless, they are limited due to the variability of wind speed and low inertia constants of between 2 to 6 s [2].

4.3. Virtual inertia provision by energy storage sources and hybrid energy storage technology

Energy Storage system can also be made to provide virtual inertia with appropriate control strategy. This provides a viable compensation for the lack of kinetic energy in renewable energy sources (RES), and it is also used to provide fast frequency regulation in case of sudden power imbalance in renewable energy sourced grid. Different types of energy storage system such as BESS, SCES, and SMES are often used based on their unique characteristics in renewable energy sourced grid in order to ensure adequate virtual inertia. Table 2 gives comparative characteristics, merits, demerits and applications of BESS, SCES, SMES, Hydrogen Storage System(HSS) and their respective hybridized form. It should be noted that FESS, SMES and SCES have similar characteristics, nonetheless, their characteristics is complimentary to that of BESS, hence a hybridized energy storage system is often preferred. The combination of SCES and BESS (lithium-ion) gives the best desirable qualities needed to provide fast inertia response, especially in renewable sourced power system [10]. Other hybridized energy storage system include BES–SMES, BES–FES, BES–SCES–FCES [12]. The hybridized energy storage system has higher power density, higher energy density, longer life cycle life, lower cost with faster response than singly sourced energy storage system.

Table 2. Comparison between BES, SCES, FES and SMES.

Energy storage system	Merits	Demerits	Application	Hybridized form	Refs.
BESS (Lithium-ion)	Small charging current, High energy density, high efficiency, fast response	Short life span (3 years), high cost, Low energy density	Electric vehicles (EV), Hybrid Electric Vehicles (HEV), AGC, PFC and LFC in Microgrid, spinning reserves, damping control	WIND-PV-BESS–SCES, BESS–SMES, HSS–BESS, WTG–BESS	[36]
Superconducting Magnetic Energy Storage (SMES):	Faster ramp rate, high power density, longer life span	Lower energy rating and lower power rating, high cost of installation,	Power smoothing and peak shaving devices	BESS–SMES, SCES–SMES	[37]
Super Capacitor Energy Storage (SCES):	High power density, fast frequency response, lower cost per KW	Short discharge duration	HVDC systems, Power–Frequency Control (PFC)	BESS–SCES, HYDROGEN–SCES	[38]
Fuel cell Hydrogen Storage System (HSS)	Higher efficiency, high energy density, low emission	Technology is still under development	Electric vehicles (EV) and Hybrid Electric Vehicles (HEV)	WT-PV-FC, HSS–BESS	[36]

4.4. *Virtual inertia in hybrid system*

The combination of renewable energy sources and energy storage systems has been used to support frequency regulation and provide system inertia in renewable energy sourced grid using the concept of virtual synchronous generator (VSG). Various hybrid systems are thus formed comprising of different renewable energy sources (RES) and energy storage system (ESS) with a suitable control mechanism in order to provide more virtual inertia in the power grid compared to single renewable energy source. For example, wind turbine connected BESS, wind turbine connected SCES, PV power plant connected BESS, PV power plant connected SCES, and Wind-PV connected BESS. In HVDC systems, SCES are usually installed at the dc-link of converters which are used as energy storage sources for inertia emulation [10].

Furthermore, Other authors have investigated the use of a combination of synchronous generator and energy storage system in order to improve system stability in power grid. For example, BESS connected synchronous condenser [33] and variable inertia flywheel (VIF) connected Diesel synchronous generator in [20,35] for providing system inertia using a suitable control scheme, however these configurations are limited because of the production of GHGs emissions [33].

5. Conclusion

This paper highlights the importance of system inertia in power system stability and further presents a comprehensive review of various system inertia contributors (synchronous generators, renewable energy sources and energy storage systems) used in renewable energy sourced grid. The characteristics (merit and demerits) and applications of various types of synchronous generators and energy storage system such as BESS, FESS, SCES, CAES, SMES, PHES, HSS and FESS were also presented. Furthermore, characteristics of hybridized energy storage system such as BES–SCES, BES–FES, and BES–SCES were highlighted, while hybrid system such as wind turbine connected BESS, wind turbine connected SCES, PV power plant connected BESS, PV power plant connected SCES, and Wind-PV connected ESS were also discussed in detail. Finally, it can be observed that hybridized system provides better characteristics than single renewable energy system, therefore the best suited hybrid system can be formed based on the desired power grid characteristics and specific power requirement. It should also be noted that FESS, SMES and SCES have similar characteristics; nonetheless, their characteristics are complimentary to that of

BESS, PHES and CAES technology, so the hybrid combination comprising of BESS and SCES could be considered best suited for fast frequency response in renewable energy sourced grid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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